INCREASING HEAT TRANSFER IN DRAG REDUCING TURBULENT FLOW

Thesis

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By

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Abstract

Drag reducing additives have great potential for many different applications today. When these compounds are added to a fluid, they decrease turbulent fluctuations as well as the energy requirements when pumping the solution. This is especially beneficial in an industrial environment where companies are constantly looking for new cost saving measures to implement. The drawback of known drag reducing solutions is that they impede the ability of the solution to transfer heat. This is an undesirable effect if heat exchangers are to be used. To test methods of increasing heat transfer, a large recirculating loop with a countercurrent shell and tube heat exchanger was used. A pulsating pump was placed before the inlet to the heat exchanger. Temperature measurements were taken with varying amounts and frequencies of pulsation in order to enhance the heat transfer in the heat exchanger.

Acknowledgements

First, I would like to thank Dr. Zakin for his help and support through the past year and a half. There were many slow and frustrating times where our research came to a stand-still, and Dr. Zakin was always patient and understanding. I would not be where I am today without his knowledge and guidance.

I would also like to thank Andy Maxson and Prathamesh Karandikar. Prathamesh has been helpful and done experiments with me since he joined the lab group in 2014. Andy joined Dr. Zakin's group around the same time I did in 2012. It was just he and I for a long time, and he has helped me through every road block I have encountered in my research.

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Chapter 1: Introduction

Drag reduction in turbulent pipe flow is a phenomenon that occurs when additives are dissolved in a solvent, causing a reduction in turbulent flow pressure losses. This can result in decreased pressure loss at the same volumetric flow rate or a larger volumetric flow rate at the same pressure loss. Two types of additives are effective: long chain polymers that align themselves with the direction of flow and self-associating low molecular weight surfactants.

The first successful commercial use of polymers in fluid flow was in the trans-Alaskan pipeline. This pipeline was built between the years 1974 and 1977, and is approximately 800 miles long with an inside diameter of forty-eight inches and a wall thickness that is 0.462 inches for 466 miles and 0.562 inches for 334 miles [1]. As the name suggests, the pipeline stretches across Alaska going from the far north Prudhoe Bay to Valdez, an all-weather port. Presently, this pipeline has shipped over 16 billion barrels of crude oil using polymers as drag reducing additives.

The drag-reducing additives were initially used to increase throughput while additional pumps were being installed in the pipeline. Without the drag-reducing polymers, the throughput of the pipeline was 1.5 million barrels a day. The addition of the drag-reducing polymers allowed the pipeline to pump 2 million barrels a day. Drag-reducing polymers are also used in firefighting to allow the water in the hose to travel further with the same amount of pressure and to give a more coherent stream.

Polymers are very valuable when used as drag-reducing agents, but they do have drawbacks. Polymers are made up of covalently bonded repeating units. The bonds between these units can break from high shear stress which occurs when going through a pump. These covalently bonded units have no way of reassociating with each other once broken, and therefore are useless after they are broken down. Drag reducing solutions also reduce the rate of heat transfer which can be useful if it is desirable to have the fluid inside the pipe insulated. However, if it is necessary to efficiently change the fluid temperature this is a drawback.

Maximum heat transfer is desired in applications like district heating and cooling systems. Primarily used in Europe, district heating and cooling systems are used to heat and cool buildings in a district in place of those buildings having their own space heaters or air conditioners. This is accomplished through using excess heat from electric power plants to heat water which is then transported throughout the district, heating all of the buildings [2]. Energy efficiency can be improved if drag reducing additives are used to reduce the amount of pumping energy needed for pipe flow.

One successful way to circumvent the issue of shear degraded polymers which do not reassociate with each other is to use drag reducing surfactant solutions. Appropriately formulated low molecular weight surfactants form long thread-like micelles – self-associating structures held together by ionic bonds. These bonds, which are not as strong as covalent bonds, reassociate with each other once broken. Therefore they don't suffer the same drawback as polymer additives. These surfactant solutions do, however, have the same issue with heat transfer, because the surfactant micelles reassociate soon after they are broken up due to high shear. This thesis will explore a novel method of enhancing heat transfer of drag reducing surfactant solutions in turbulent tube flow.

Chapter 2: Literature Review

2.1 Fanning Friction Factor and the Reynolds, Prandtl, and Nusselt Numbers

The discovery that polymer additives could be used to reduce drag was reported in 1949 by Toms [3]. He observed that only 10 parts per million of poly(methylmethacrylate) was required to reduce drag of a monochlorobenzene solution by 30 to 40 percent. To quantify the amount of drag reduction taking place in a solution, the Fanning friction factor is used. The equation for the Fanning friction factor is:

$$f = \frac{\Delta p}{\rho V^2}\frac{R}{L} \tag{1}$$

where Δp is the pressure drop across a specified distance L, R is the radius of the pipe, ρ is the density of the fluid, and V is the velocity of the fluid inside the pipe.

In order to make a useful comparison, the Fanning friction factor for water must be obtained. To find the corresponding Fanning friction factor for water at the same Reynolds number, the Karman-Nikuradse equation for turbulent flow in smooth pipes with a circular diameter can be used [7]. This correlation is:

$$\frac{1}{\sqrt{f}} = 0.86\ln\left(Re\sqrt{f}\right) - 0.8 \tag{2}$$

The Fanning friction factor is a function of another dimensionless number, the Reynolds number. The Reynolds number of a fluid represents the ratio of inertial forces to viscous forces [4]. There are three regions used to characterize flow based on Reynolds number: laminar flow, transition flow, and turbulent flow [5]. Laminar flow occurs in tubes between a Reynolds number of 0 to ~2100. The flow is smooth and viscous forces dominate the inertial forces. Turbulent flow occurs when the Reynolds number of a fluid is greater than ~4000. The flow in this region is chaotic and without order, and the inertial forces dominate the viscous forces. Transition flow occurs between ~2100 and ~4000. The flow in this region is less defined and is a mix of laminar and turbulent flow. Reynolds number generally characterizes the type of flow exhibited by a fluid. The general equation for calculating the Reynolds number is:

$$N_{Re} = \frac{\rho V L}{\mu} \tag{3}$$

where ρ is the density of the fluid, V is the linear velocity of the fluid, L is the characteristic length, and μ is the dynamic viscosity of the fluid. For a fluid going through a pipe, Equation 3 becomes Equation 4:

$$N_{Re} = \frac{\rho V D}{\mu} \tag{4}$$

where the only change is that the characteristic length, L, becomes the diameter of the pipe, D.

With the value of the Fanning friction factor known for water and the measured values of f for the drag reducing solution, the drag reduction percentage is then found using Equation 5:

$$Drag\ Reduction\ \% = \frac{f_{water} - f}{f_{water}} \times 100\% \tag{5}$$

There are other dimensionless numbers – such as the Prandtl number – which can be used to predict the heat transfer ability of fluids. The Prandtl number is defined as the ratio of the shear component of momentum diffusivity to the heat diffusivity. This compares the thickness of the hydrodynamic layer to the thermal boundary layer [10]. The Prandtl number is calculated using Equation 6 below.

$$N_{Pr} = \frac{\mu/\rho}{k/\rho c_p} \tag{6}$$

which simplifies to Equation 7 below.

$$N_{Pr} = \frac{\mu c_p}{k} \tag{7}$$

c_p is the heat capacity, k is the thermal conductivity, and μ is the dynamic viscosity. As the Prandtl number gets larger, the fluid is more viscous and therefore conductive heat transfer dominates. The smaller the Prandtl number, the more convective heat transfer dominates [11].

The Nusselt number is also used to analyze heat transfer for fluids. The Nusselt number compares the heat transfer coefficient to the thermal conductivity using Equation 8 [10]:

$$N_{Nu} = \frac{hD}{k} \tag{8}$$

where h is the heat transfer coefficient in Watts per meter squared per degree Kelvin, and all other variables are previously defined. The convective heat transfer coefficient is not typically known. Therefore other methods must be used to estimate the Nusselt number. The formula used to estimate the Nusselt number changes based on the dimensions and geometry of the heat exchanger, the Reynolds number, the Prandtl number, the type of flow inside the heat exchanger, and other factors. The conditions of the heat exchanger used in this experiment require Equation 9 to be used to determine the Nusselt number [10].

$$N_{Nu} = 0.027 N_{Re}{}^{0.8} N_{Pr}{}^{\frac{1}{3}} \left(\frac{\mu_b}{\mu_w}\right)^{0.14} \qquad (9)$$

2.2 Surfactants

As previously mentioned, there are two popular groups of drag reducing agents: polymers and surfactants. Using polymers as drag reducing agents means they must be continually injected into the system due to their structures breaking down from shear stress and temperature effects [6]. This thesis deals with a system in which the fluid is continually recirculated through a gear pump and also is subjected to heat. Therefore polymers are not considered. Instead, the surfactant Ethoquad O/12 was used. Ethoquad O/12 is the common name for oleylmethylbis(2-hydroxyethyl) ammonium chloride. Figure 1 below shows the chemical structure of Ethoquad O/12

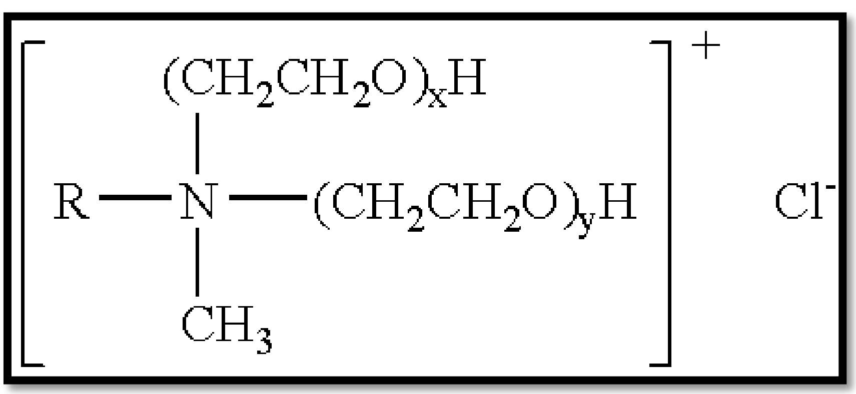

Figure 1: The chemical structure of Ethoquad O/12

Ethoquad O/12, in the presence of the counterion sodium salicylate, is able to form threadlike micelles. Figure 2 below shows the micelle structure [7].

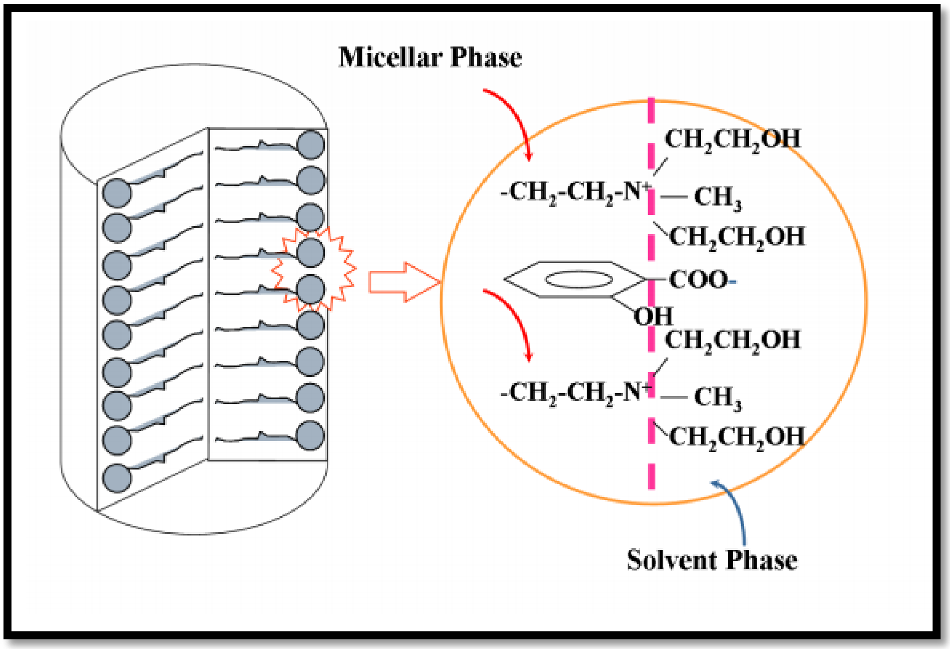

Figure 2: The micellar structure of Ethoquad O/12 in the presence of sodium salicylate.

As displayed above, the polar end of the molecule aligns itself on the outside of the rod with the nonpolar end on the inside. These molecules then form a circle with the polar head on the hydrophilic outside and the hydrophobic tails on the inside, and the thread extends.

Surfactants will only enter the micellar phase at certain concentrations. This concentration is referred to as the critical micelle concentration, or the CMC. Above this concentration, the surfactant will form spheres. There is a second CMC at which the surfactant will change from spheres into the threadlike structure described above [8]. Figure 3 below shows a schematic of the phase diagram for surfactant solutions [17].

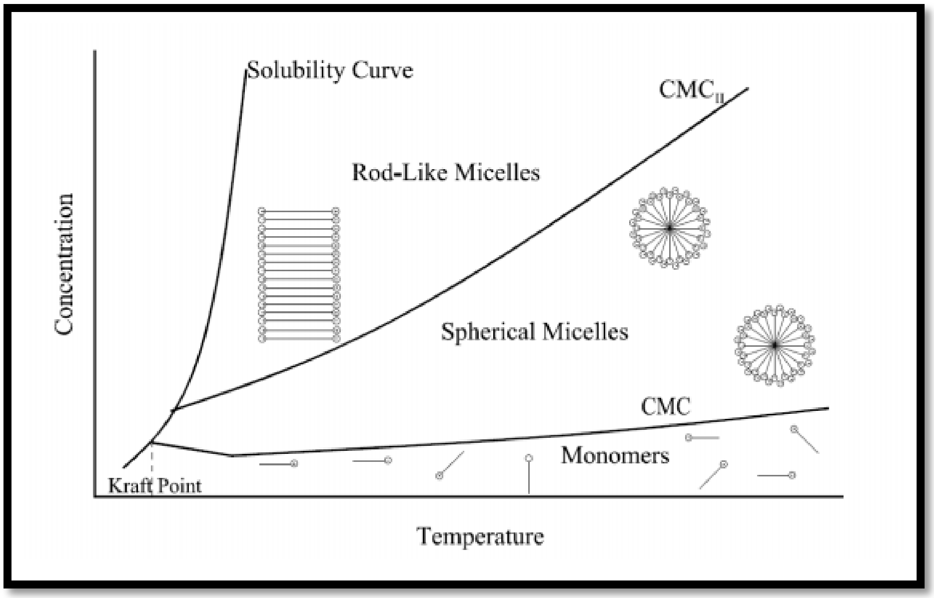

Figure 3: Phase diagram of concentration versus temperature for surfactants.

Without the use of a counterion, surfactant solutions would not form micellar structures for drag reduction purposes at low concentrations. Counterions like sodium salicylate are added in higher than equimolar concentrations compared to the surfactant to account for the sodium salicylate that dissolves in water. The counterion helps disperse charges on the polar ends of the surfactant molecules and lets them form long wormlike micelles, as well as increase the critical temperature and critical Reynolds number at which drag reduction loses its effectiveness [11].

2.3 Heat Transfer

There are three main modes of heat transfer: conductive heat transfer, convective heat transfer, and radiation. Conductive heat transfer is the transfer of energy between adjacent molecules. This type of heat transfer occurs when a temperature gradient exists in a solid, liquid, or gas [10]. There are two types of convective heat transfer; natural convection and forced convection. Natural convection occurs due to a temperature difference between a fluid and a solid, and heat transfer occurs due to density differences. Forced convection occurs when a fluid is forced into contact with a solid surface by mechanical means [10]. The final medium of heat transfer is through radiation. Radiation occurs through electromagnetic energy propagating through space. Radiation does not need a state of matter to travel through [10]. In this experiment, only forced convection is used as a means of heat transfer though there could be small heat losses due to the other types of heat transfer.

As mentioned earlier, the ability of a solution to transfer heat decreases when a drag reducing additive is used. The reduction in heat transfer is due to the viscous sub-layer that forms near the wall of the tube. In a fluid that experiences drag reduction via the presence of a drag reducing additive, the viscous sub-layer increases in size. This increase in size leads to an increase in thermal resistance, and therefore a decrease in heat transfer to the bulk fluid [12]. If this viscous sub-layer can be disturbed or thinned, the heat transfer should increase in the heat exchanger.

Several methods have been studied to increase heat transfer in tube-in-tube flow including vibration and pulsation. When pulsation is used, the idea is that axial flow will increase inside the heat exchanger. The increased axial flow – as long as it is at a sufficient amplitude and frequency – should increase the velocity of the fluid near the wall. The increase in velocity profile near the wall decreases the thickness of the viscous sub-layer, and thus decreases the thermal resistance in the tube. However, the amplitude of the pulses must be large enough to induce reverse flow in the heat exchanger. Figure 4 below displays the results of a study investigating the effects of pulsation on the Nusselt number [14].

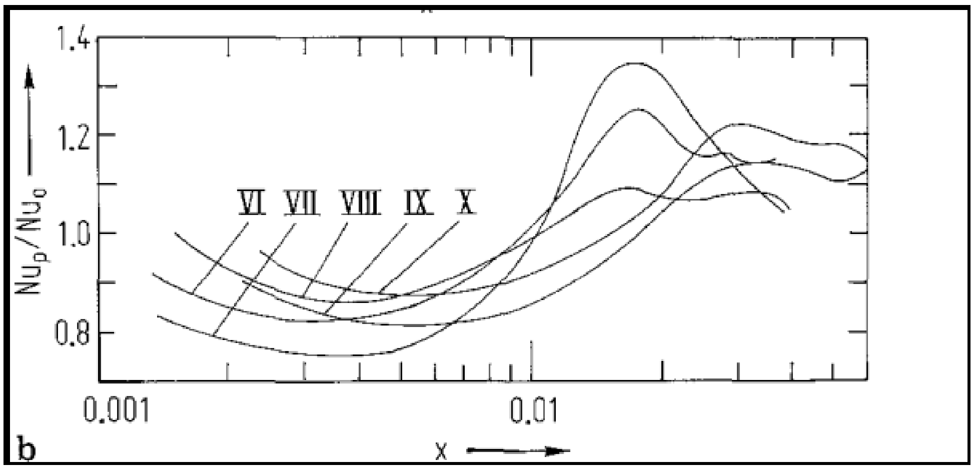

Figure 4: Ratio of the Nusselt number under pulsation to the Nusselt number without pulsation against a characteristic distance of the pulsation inlet to the heat exchanger.

The x-axis is a characteristic distance representing the distance from the injection point to the beginning of the heat exchanger compared to the entire length of the heat exchanger. The y-axis is the ratio of Nusselt numbers of flow with pulsation to flow without pulsation. The different lines in Figure 4 represent different amplitudes of pulses. The figure shows that increasing heat transfer is possible using flow pulsation. However, the figure was produced under different conditions from those studied here. The Reynolds number range studied by those investigators was lower than the region in this study. Additionally, their data were produced using only water as opposed to a fluid with a drag reducing additive in it. This study was designed to obtain similar data for a fluid containing a drag reducing additive which reduced heat transfer compared with water.

Chapter 3: Experimental Methodology

3.1 Solution Preparation with Drag Reducing Agent

To prepare the fluid to be run in the recirculating loop, the drag reducing agent and counterion were added to six liters of deionized water. The quantities used were weighed using an analytical balance. 21.79 grams of Ethoquad O/12 was added to give a concentration of 5 millimolar Ethoquad O/12. 12.01 grams of the counter ion – sodium salicylate – were then added to give a 12.5 millimolar concentration. The solution was then stirred for 24 hours using a mixer to ensure full dispersion of the Ethoquad O/12 and sodium salicylate in the solution.

3.2 Heat Transfer Trial Process

Once the solution was prepared, it was funneled into the recirculating loop. A figure depicting a general schematic of the first recirculating loop setup is shown in Figure 5 below.

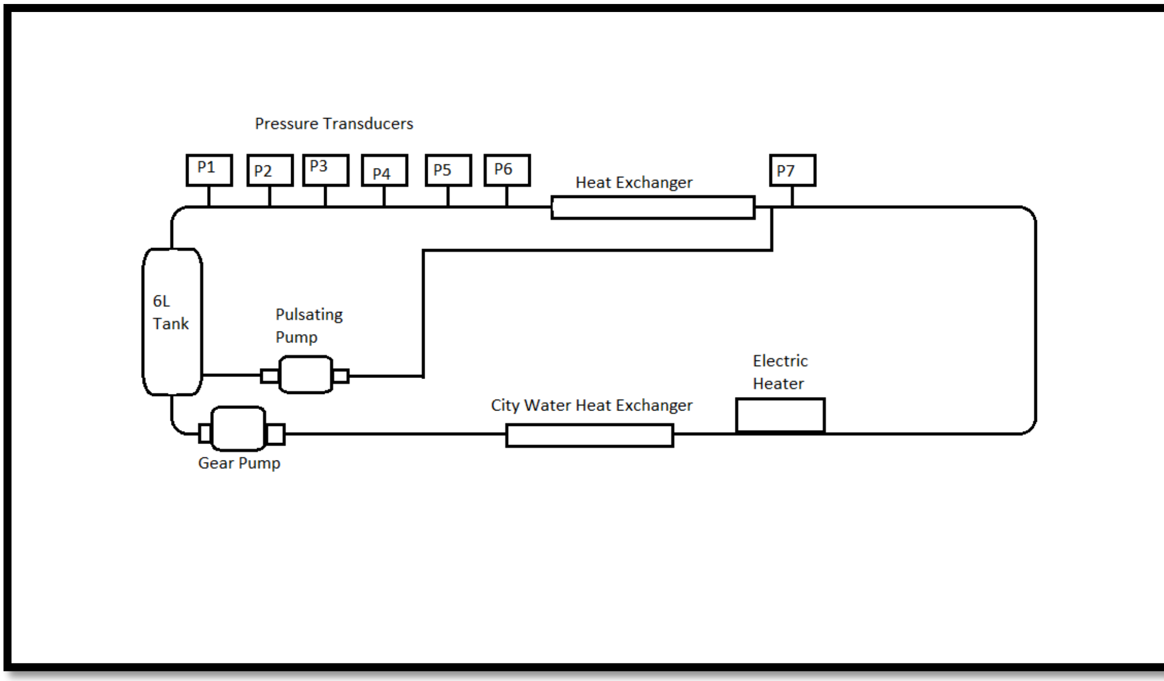

Figure 5: Schematic of the first recirculating loop setup.

The Ethoquad O/12 solution was slowly funneled into the 6L tank. After all of the solution was fed into the tank, the gear pump was switched on. The new solution was circulated for several minutes without taking data points in order to rid the system of air bubbles. The hot water bath for the annulus part of the heat exchanger was heated up concurrently. The bath was set at 55 degrees Celsius. The solution circulating through the recirculating loop was kept at 30 degrees Celsius. The area that contains the heat exchanger is the only section of the recirculating loop that is insulated, therefore the recirculating loop was susceptible to heating or cooling depending on what the ambient temperature was. A hotter ambient temperature would cause the fluid in the recirculating loop to have a net gain of energy, therefore increasing the temperature in the loop past 30 degrees Celsius. A colder ambient temperature would cause the opposite effect. A heat exchanger using city water was used when the ambient temperature was too warm because the city water was consistently below 30 degrees Celsius.

The setup of the shell and tube heat exchanger - along with thermocouple placement - is shown in Figure 6 below.

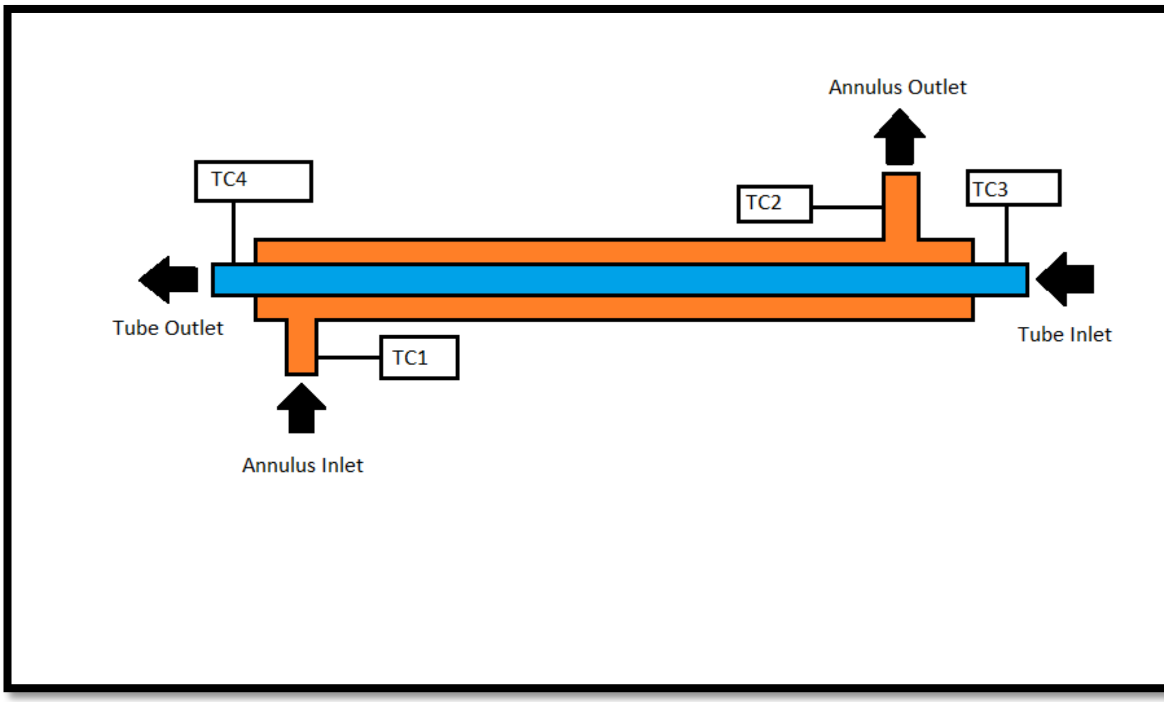

Figure 6: Shell and tube heat exchanger and thermocouples.

The heat exchanger used was a countercurrent shell and tube, single pass heat exchanger. TC1 and TC2 measured the annulus inlet and outlet temperatures, respectively. TC3 and TC4 measured the tube inlet and outlet temperature, respectively. Inside the heat exchanger, heat transfer was taking place at the boundary between the tube and the annulus. The thermocouples were positioned at the center of the tube. The Ethoquad O/12 solution reduces heat transfer to the tube and there is a temperature gradient from the tube wall to the center. Therefore the center of the tube is not an accurate representation of the average temperature of the solution in the tube after it goes through the heat exchanger. Without good mixing, the thermocouple would give a low reading, therefore a static mixer was placed just before TC4 in order to mix the fluid to obtain a uniform fluid temperature to improve the accuracy of the temperature measurements.

After the system reached steady state, the piston pump – which provides the pulsation – was turned on. In early experiments the piston pump took solution from the 6 liter holding tank and injected it into the system just before it entered the heat exchanger. After steady state was reached with the gear pump and the piston pump on, data points were collected for the heat transfer experiment.

A data acquisition system was used to transfer the data obtained by the thermocouples to a computer. When a trial was run, the data acquisition system collected data at a rate of 300 samples per second for two seconds for a total of 600 data points for each of the four thermocouples. For each thermocouple, the average of the 600 data points was used as a representative temperature for the data set. Figure 7 below shows the distribution of a sample set of data points obtained from the thermocouples.

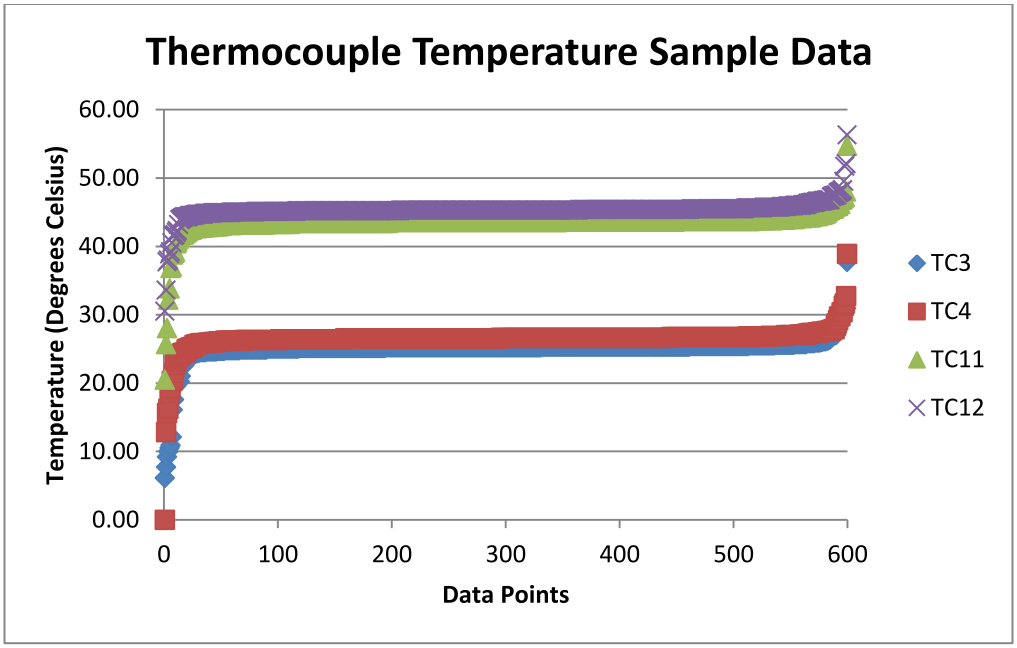

Figure 7: Sample data points obtained from thermocouples.

The distribution above shows that taking the average of the 600 data points was an accurate way of describing the temperature in the annulus or the tube. Although there were outliers for all four sets of data, the outliers occurred on both sides. Additionally, the outliers make up a very small percentage of the data points and contribute very little to determining the average temperature read by the thermocouples.

The pulsating pump used in heat transfer experiments only has variable frequency. This frequency is changed by a knob, and can be changed from 0% pulsation to 100% pulsation. To convert these percentages into frequencies, the amount of pulses were counted over a period of time, and then this was converted into RPM. This was done for several of the lower frequencies, then extrapolated using a best fit line for the higher frequencies. Table 1 below shows these frequencies.

Table 2: The estimated RPM for a given percent pulsation.

Percent Pulsation	Estimated RPM
10	110
20	312
30	514
40	716
50	918
60	1120
70	1322
80	1524
90	1726
100	1928

3.3 Alternate Setups

Different setups of the recirculating loop were used in order to see if better results could be obtained. These different setups involved changing the inlet of the piston pump or how the piston pump operates. Figure 8 below illustrates the second setup that was used for pulsation experiments.

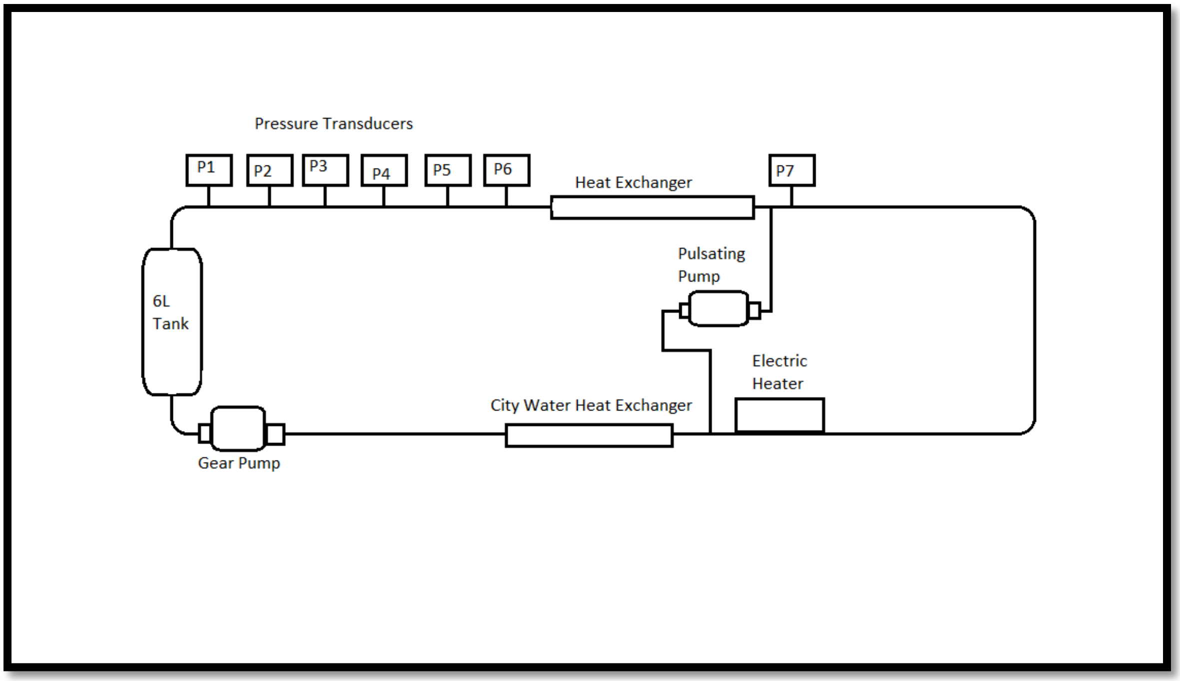

Figure 8: The second setup used in pulsation experiments.

While the first setup took fluid from the 6 liter holding tank, the second setup pulled fluid from the tube after it goes through the city water heat exchanger. When the first setup pulled liquid from the 6 liter tank, it was pulling in liquid that was not at a uniform temperature as the tank did not have a way of mixing the liquid inside it, and there was no way to be able to tell if the tank fluid temperature was uniform. Additionally, the fluid in the 6 liter holding tank – and therefore the water pulsing into the tube – was at a higher temperature than the fluid entering the heat exchanger. The fluid going through the pulsating pump in the first setup was close to the temperature that it had when leaving the heat exchanger. This difference in temperature could have adverse effects on the ability of the thermocouples to measure the correct temperature.

Additionally, the amplitude of the pulses entering before the heat exchanger could be affected by the distance. The longer the pipe that transfers the liquid from the piston pump to the inlet of the heat exchanger, the less pressure there is at the heat exchanger inlet, and therefore the pulses have less effect. Figure 9 below displays a diagram of the third heat exchanger setup that was used.

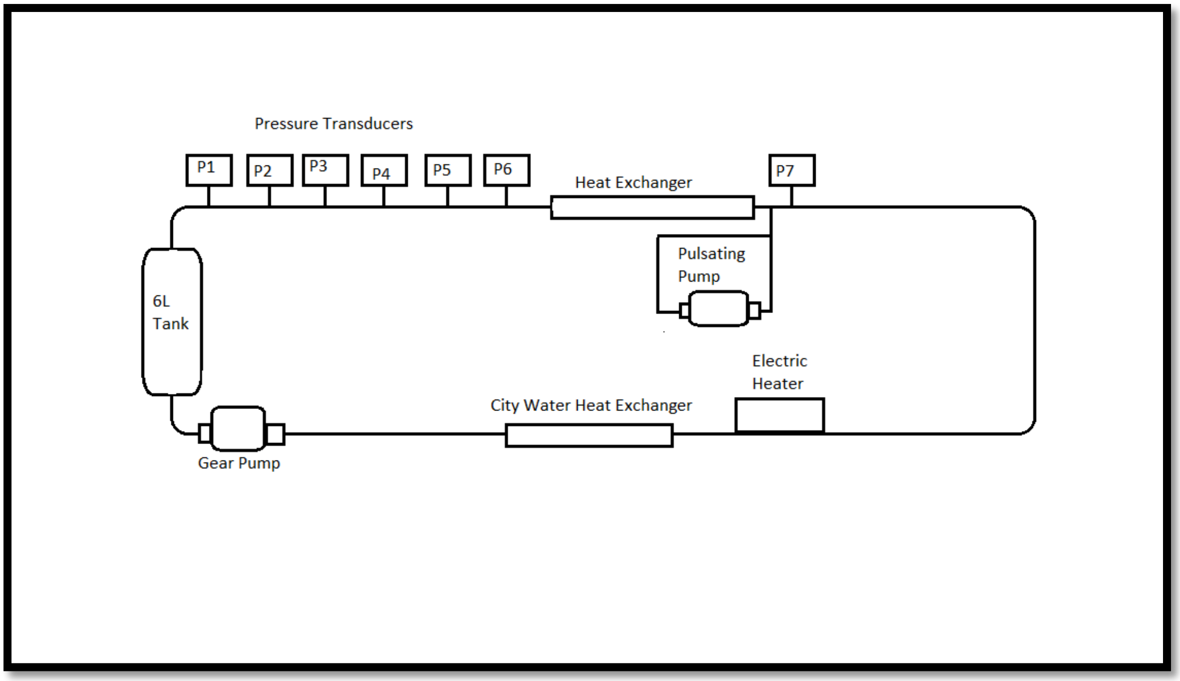

Figure 9: Schematic of the third heat exchanger setup used.

For the third setup, the pulsating pump draws in liquid at the same spot it injects it. The potential benefits of this setup are similar to that of the second setup. The temperature difference issue present in the first setup is partially alleviated by the second, however it is completely alleviated in the third. The liquid being injected is at the same point it is being extracted from, therefore the temperature difference is negligible. The same is true with the amplitude of the pulses. The second setup greatly decreases the distance of the piston pump inlet to the injection point from the heat exchanger compared to the first setup. The third setup should have no loss in amplitude. Additionally, the pump should contribute no net increase in flow. Because the pump takes in liquid from the same point at which it injects it, there is no net change in flow. The first setup pulls liquid from the 6 liter holding tank, increasing the flow rate of the tube compared to when the piston pump is not on. This change in flow rate causes data to be more difficult to compare because the Reynolds number for a certain gear pump setting will be different when the piston pump is on compared with when it is off. The third setup eliminates this issue because the lack of change in average flow rate when the piston pump is activated means the Reynolds numbers will not change, making the data between pulsation and non-pulsation easy to compare.

3.4 Data Analysis

After a trial was run and temperature data as well as volumetric flow rate data were gathered, the data were analyzed. First, the average temperatures for the tube and the annulus were calculated from the thermocouple readings and recorded. Next, the Microsoft Excel spreadsheet determined the density in kilograms per liter for the average temperatures in the tube and in the annulus. The volumetric flow rate in gallons per minute was converted to liters per second and multiplied by the density to get the mass flow rate. The Microsoft Excel spreadsheet then determined the heat capacity of water at the specific temperatures of the annulus and the tube. The mass flow rate was then multiplied by the heat capacity to get the heat transfer rate for the annulus and the tube. The Reynolds number was calculated only for the tube side. The volumetric flow rate in gallons per minute was converted to a linear velocity in meters per second and with the density and viscosity was used to calculate the Reynolds number. The heat transfer rate was then plotted against the Reynolds number.

Chapter 4: Calibration

The thermocouples were capable of taking many readings within a short period of time with reasonable precision; however these readings were not representative of the actual temperature inside the annulus or the tube. Each thermocouple's average temperature reading was often off by more than half a degree – compared to a thermometer reading - which would result in a very large error in heat transfer rate. To fix this error, several different forms of calibration were employed in order to obtain more accurate results.

The first calibration process involved all four thermocouples and a water bath. The water bath had a digital readout that displayed the temperature accurate to a tenth of a degree Celsius, and it also had an electric heater built in. The water in the bath was initially cooled to twenty degrees Celsius. The four thermocouples were then placed into the water bath close to each other in order to make sure the thermocouples were all measuring the same temperature. The bath could vary in temperature throughout, therefore it was important to put the thermocouples as close to each other as possible. A glass thermometer – precise to 1 degree Celsius - was also placed with its tip near the four thermocouples in order to get the exact temperature of that area. The temperature of the bath was then constantly increased and readings were taken every half a degree Celsius.

This calibration had some drawbacks. When the temperature of the water bath started to approach the set temperature, the internal cooling system of the bath would turn on. This caused the bath to take several minutes to reach the set temperature. To get around this issue, the set temperature of the bath was increased before the bath reached the original set temperature. Doing this caused the hot water bath to be in a transient state which increased the chance that the temperature reading being taken was not the true temperature of the water bath.

A second, improved calibration procedure was used to eliminate potential errors that arose from the first calibration procedure. One of the thermocouples – TC4 - was taken to be the true temperature of the water bath. This thermocouple often read very close to the temperature read on the thermometer, and therefore eliminated the extra step of reading the thermometer. It also eliminated human error in reading the thermometer. Instead of placing the thermocouples in a water bath and increasing the temperature constantly, water was heated to 55 degrees Celsius and placed in a jar. The four thermocouples were also placed in the jar. Ice was then added to decrease the temperature of the water. The water was stirred to ensure a uniform temperature profile. After the ice cube that was added had melted, temperature readings of TC4 were taken until temperature reached steady state. Then the other thermocouple readings were recorded. More ice was added, and the process was repeated across the entire temperature range of 55 degrees Celsius to 20 degrees Celsius. Using this calibration method, Figure 10 on the next page was produced where the heat transfer percent error – or Q percent error – was calculated using Equation 10:

$$Heat\ Transfer\ \%\ Error = \frac{Q_{annulus} - Q_{tube}}{Q_{annulus}} \tag{10}$$

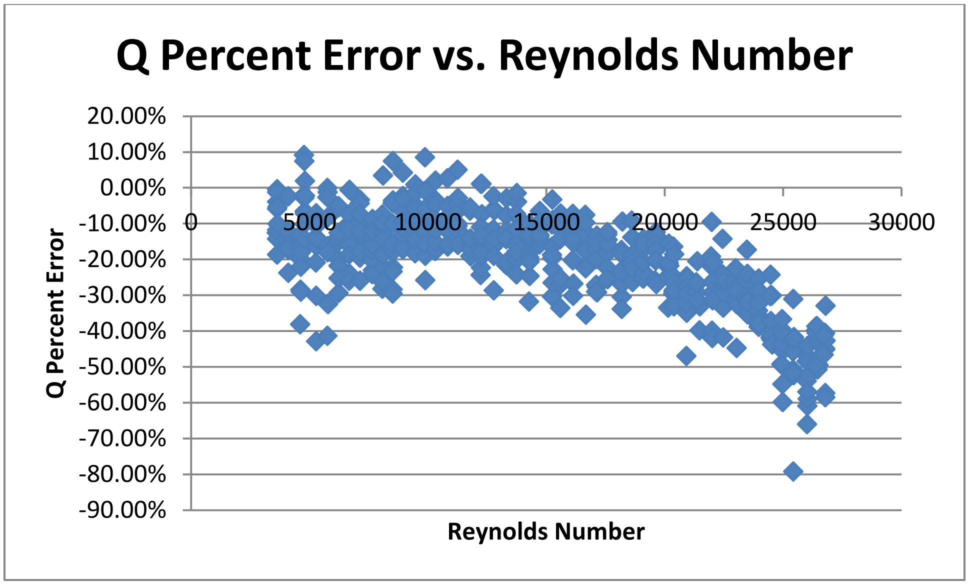

Figure 10: A plot of the Q percent error versus Reynolds number.

The data shown in Figure 10 suggest that the calibration technique was unsuccessful. As the Reynolds number increases, the heat transfer percent error became more and more negative. Because of the way heat transfer error is calculated, this means that the data suggest the tube is gaining more heat than the annulus is losing, which is not possible.

There were serious issues present for both calibration techniques described above. The calibration procedures were far too time-consuming. To accurately measure every degree over a forty degree range by holding the water bath at a constant temperature for calibration every one degree took several hours. This would be acceptable if the calibrations only had to be done a few times a year. However it was found that this was not the case. The calibration had to be done every day. The ambient temperature plays a role in the calibration of the thermocouples. As mentioned earlier, the room the equipment was in was not temperature controlled. Through further research, it was found that the thermocouples should use "cold junction compensation" in order to measure temperatures. Figure 11 below displays a diagram detailing how the thermocouples used in this research function [9].

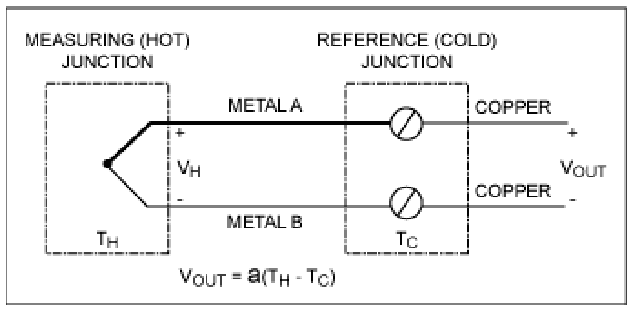

Figure 11: Diagram of configuration of thermocouples to determine temperature.

The measuring (hot) junction and the reference (cold) junction both generate a voltage. The difference between these two voltages is a measure of the temperature difference. The measured temperature is then determined by adding the temperature difference voltage to the reference temperature voltage. The setup used for this experiment causes the reference temperature measured by the cold junction to be a function of the ambient temperature [9]. With this information, it was concluded that instead of calibrating only a few times a year, a calibration would have to be done every day in order to obtain accurate data. Therefore, the calibration methods described above could not be used.

The next method used was a one point calibration. To employ this method, an assumption had to be made. The relationship between the measured temperature of the thermocouple and the actual temperature is not linear. However, the two thermocouples on the tube side only measure between 30 and 33 degrees Celsius, and the two thermocouples on the annulus side only measure between 52 and 55 degrees Celsius. Thus, it can be assumed that because these thermocouples are measuring over such small ranges, the relationship between the measured temperature and the actual temperature was approximately linear. Therefore, one data point was taken for the tube side thermocouples near 30 degrees, and one data point was taken for the annulus thermocouples near 55 degrees. Data points were taken using this calibration method and Figure 12 below was generated.

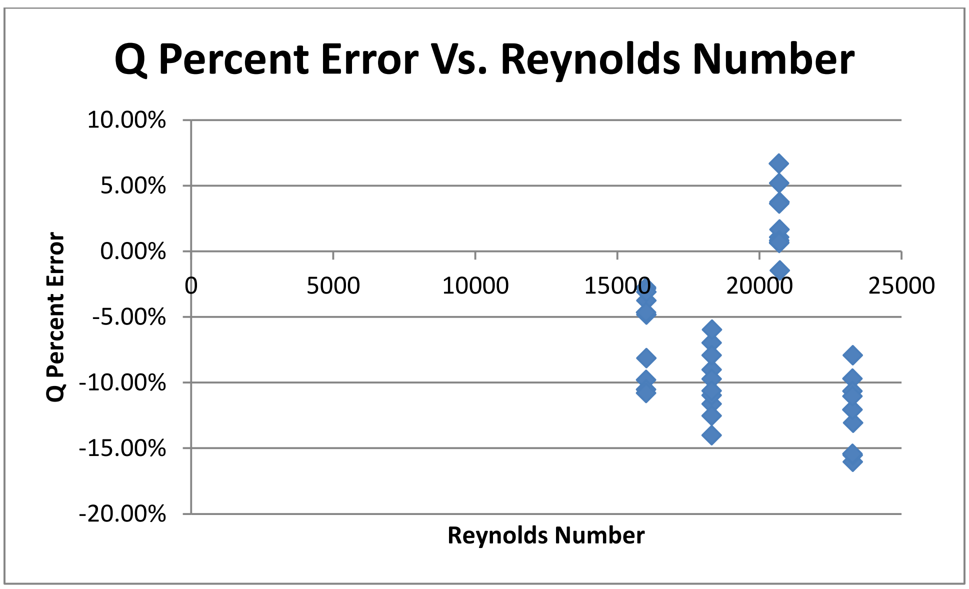

Figure 12: Heat transfer percent error versus the Reynolds number for the one point calibration.

These data suggest that the one point calibration method worked better than previous methods, but it did not give accurate values of temperature. The consistent negative error was unacceptable. As the points stray from the one calibration point taken, one of the thermocouples could deviate as much as 0.2 degrees from the other thermocouple paired with it as seen in the sharp decrease in percent error.

A final calibration method was used to correct the errors seen in the one point calibration, but which would still be relatively quick. Instead of taking only one point, two points were taken for the tube side and the annulus side. The tube side had a point for the coldest temperature it was expected to see, and the hottest temperature it was expected to see. The same went for the annulus. One thermocouple from the tube side and one from the annulus side were taken to represent the actual temperatures. Then, the other thermocouple would have the line made from its two points fitted to the line of the other thermocouple, therefore minimizing error.

Chapter 5: Results and Discussion

5.1 Setup 1

The first setup used for this research involved the piston pump pulling fluid from the 6 liter tank and injecting right before the heat exchanger as was described previously. Figure 13 below shows the data obtained for no pulsation and 10% pulsation with Ethoquad O/12 and sodium salicylate in the system.

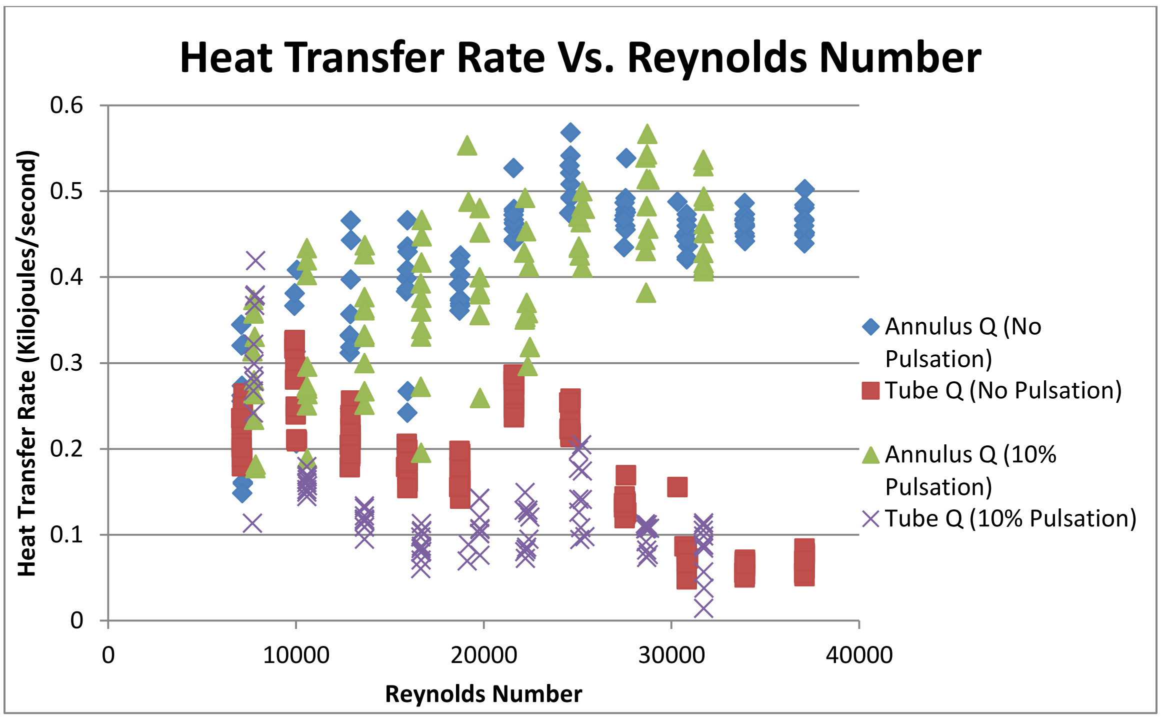

Figure 13: Heat transfer rates for the tube and the annulus with no pulsation and 10% pulsation for the first setup.

The data above show that the annulus is losing heat at a much higher rate than the tube is gaining it both with and without pulsation. The main focus of this research is on increasing the heat gained in the tube, and not the heat lost by the annulus. Therefore, the same plot was generated without the heat lost by the annulus, making it easier to read. Figure 14 and Figure 15 show the data for the tube with and without pulsation, and the average of those points, respectively.

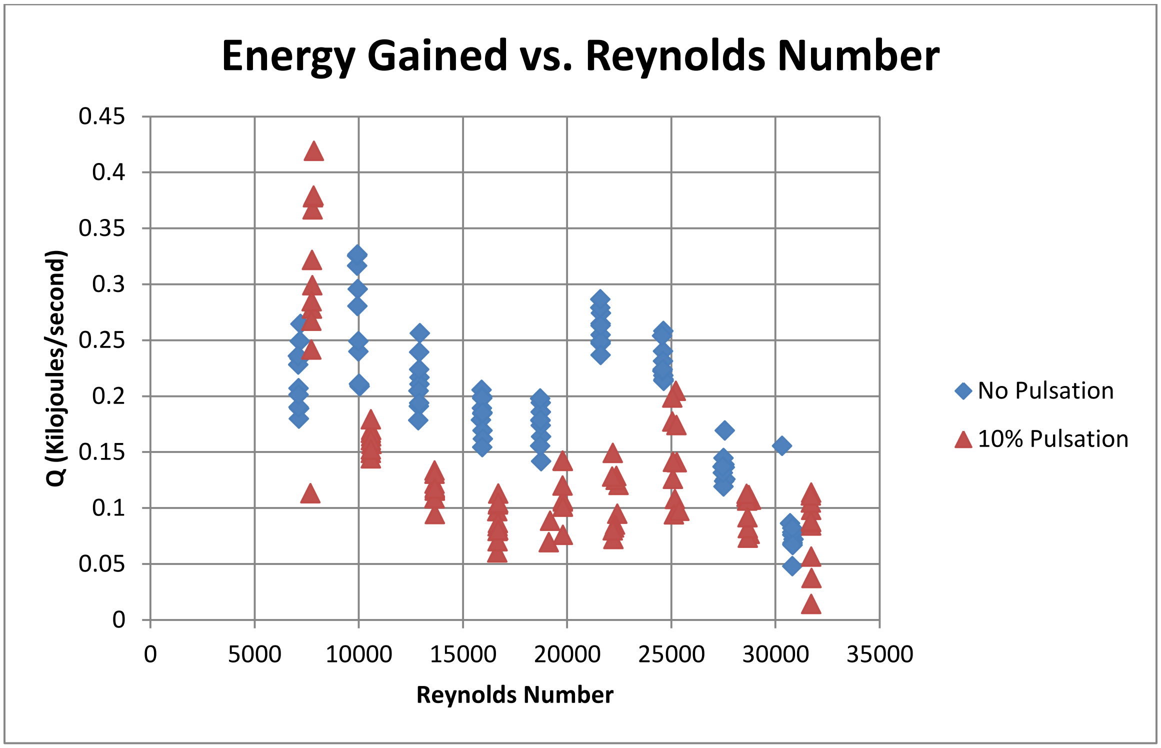

Figure 14: Data for the heat gained in the tube with and without pulsation for the first setup.

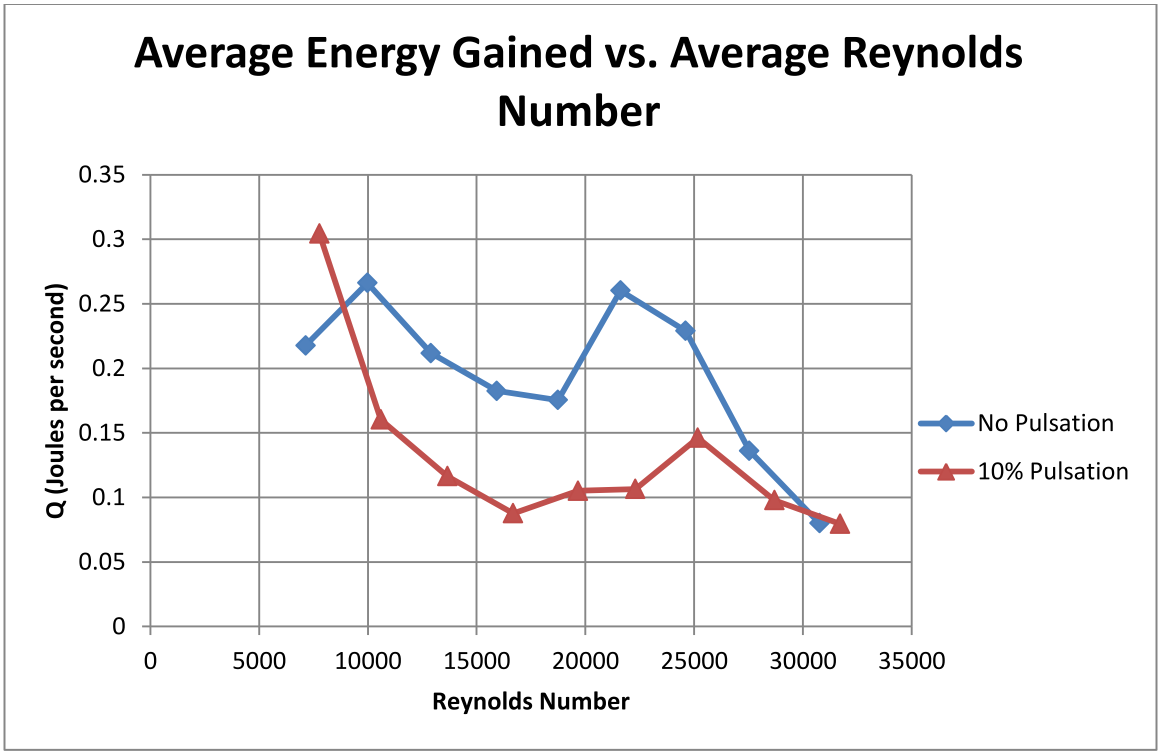

Figure 15: Data for the average heat gained in the tube with and without pulsation for the first setup.

The data above show that pulsation was not successful in increasing the heat transfer in the tube. The heat transfer rate actually decreased for every point except for the first. Figure 14 shows that the variance for this first point was very high, therefore it is not certain that heat transfer is increased in this region either. Additionally, the Reynolds number of that point was lower than the minimum Reynolds number of concern (10000).

The drastically lower heat transfer rate suggested that the setup was flawed. The long distance from where the fluid was pulled from the tank to the injection point likely led to a large pressure drop and pulses with very small amplitudes. Additionally, the liquid in the 6 liter holding tank was warmer than the liquid near the injection point, leading to inconsistent temperature readings. The pulsating pump can result in backwards flow, which would cause the warm fluid from the tank to be measured by the thermocouple making the calculated amount of heat transfer small.

5.2 Setup 2

The second setup involved pulling fluid from the tube after it had passed the city water heat exchanger and injecting it into the same spot before the heat exchanger. This change in setup increases the amplitude of the pulses as well as maintains the pulsating flow at the same temperature as the fluid in the tube. Figure 16 below shows the data obtained for no pulsation and 50% pulsation when Ethoquad O/12 and sodium salicylate were in the system.

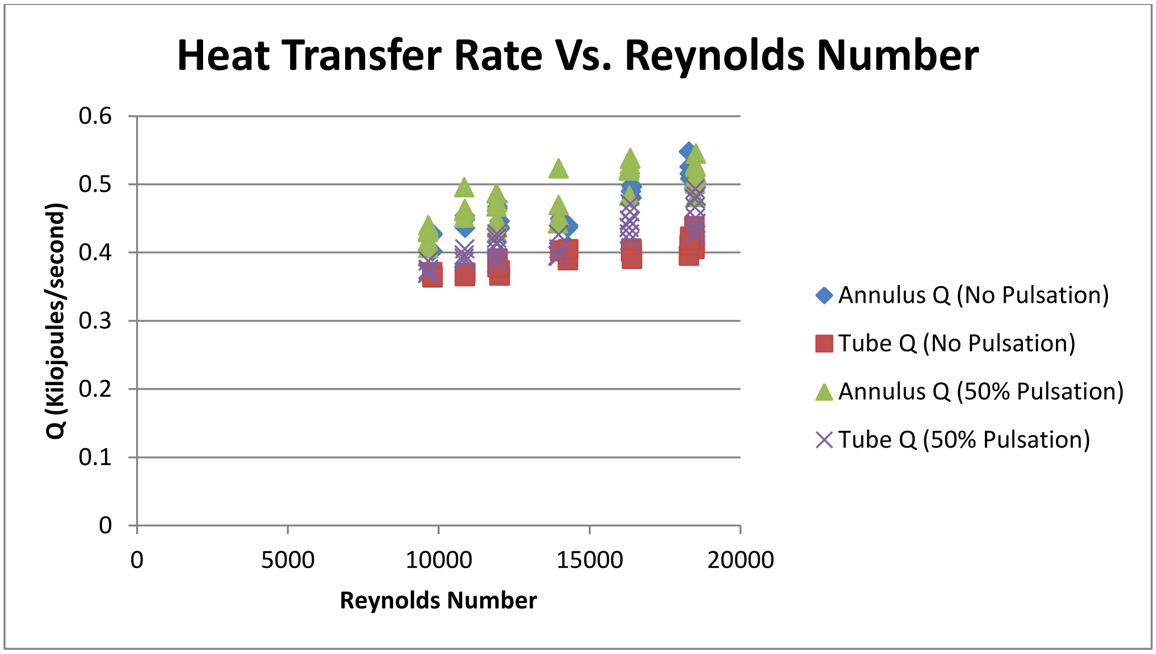

Figure 16: Data for the heat transfer rate for the tube and the annulus with no pulsation and 50% pulsation for the second setup.

The data above show a distinct difference between the first and second setup. The difference between the heat lost by the annulus and the heat gained by the tube in the heat exchanger is much smaller than what was seen for the first setup and thus this setup is more accurate. Figure 17 and Figure 18 show the data for the tube with and without pulsation, and the average of those points, respectively.

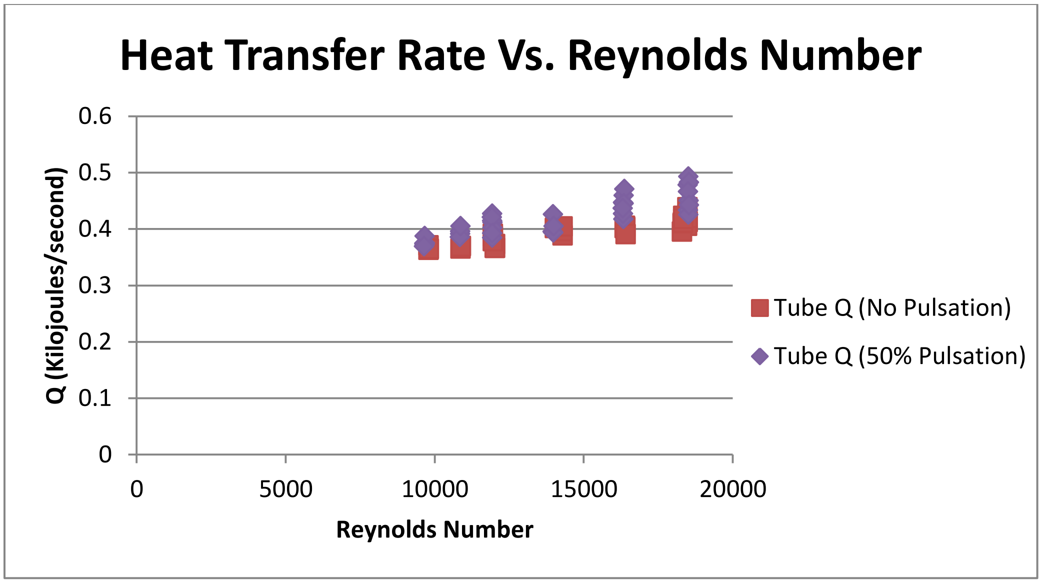

Figure 17: Data for the heat gained with and without pulsation for the second setup**.**

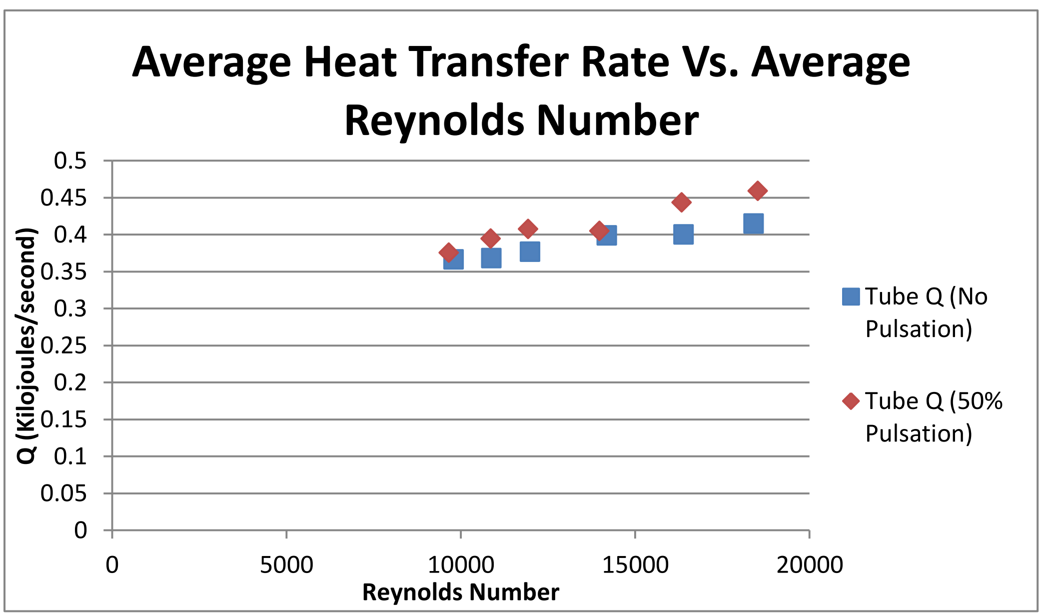

Figure 18: Data for the heat gained in the tube with and without pulsation for the second setup.

The figures show that for each Reynolds number, the heat transfer to the tube is increased with pulsation. In general, as the Reynolds number increases, the percent increase in heat transfer to the tube also increases. Additionally, Figure 17 shows that the variance of the data was low, therefore the data indicate that for this setup, pulsation will increase heat transfer moderately.

5.3 Setup 3

In the third setup, the point at which fluid is pulled from and the point it is injected into are the same. This change in setup removes concern about a difference in temperature between the injected fluid and the bulk fluid as well as concerns about decreasing amplitude because of pressure losses. Figure 19 shows data for variable amounts of pulsation in the Ethoquad O/12 and sodium salicylate system.

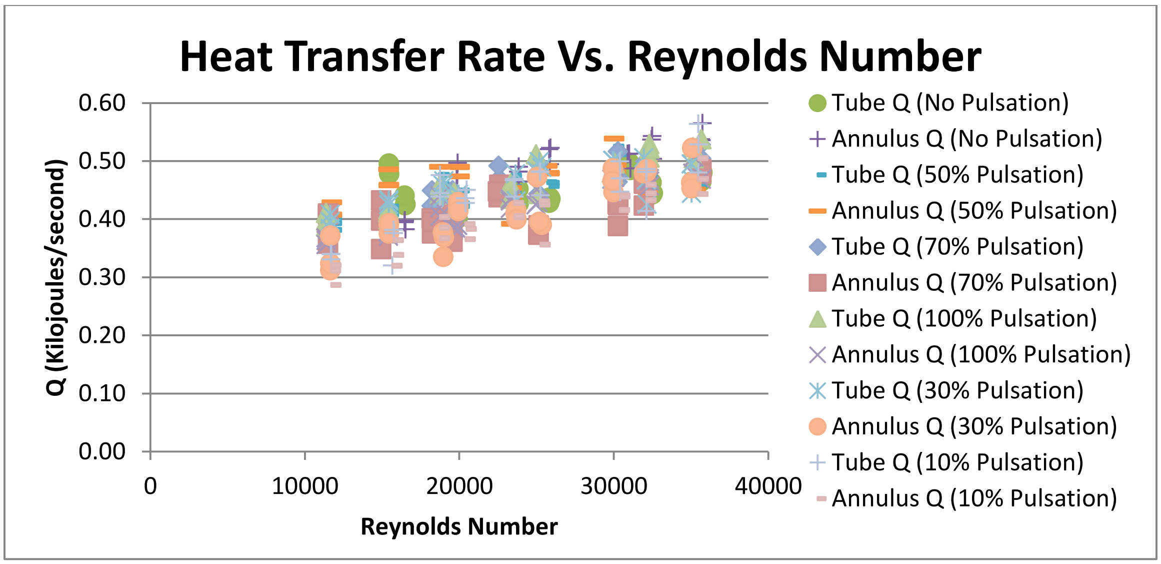

Figure 19: Data for the heat transfer rate for the tube and the annulus with varying amounts of pulsation for the third setup.

Figure 19 shows that the annulus and tube heat transfer rates are close to each other as they were in the second setup, indicating the measured results obtained in this study to be valid. Figure 20 and Figure 21 below show the data for the tube with varying amounts of pulsation, and the average of those points, respectively.

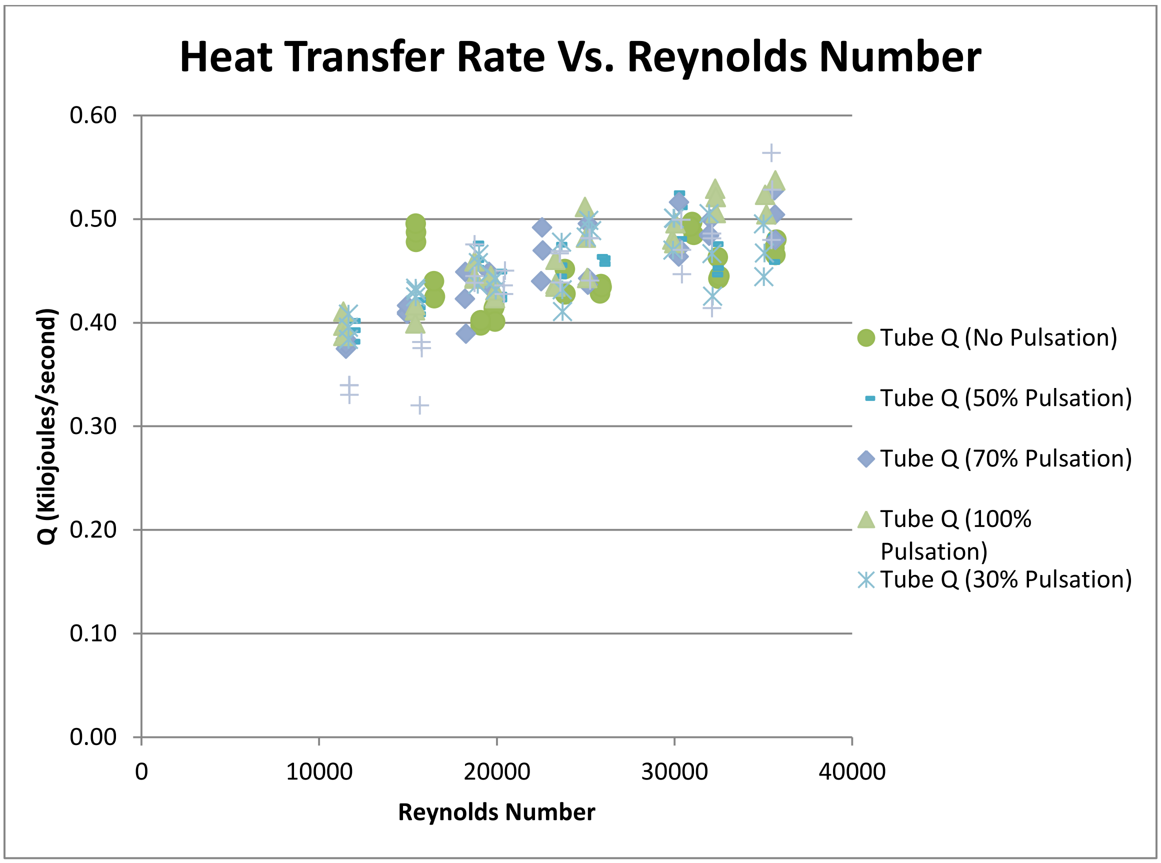

Figure 20: Data for the heat gained in the tube with varying amounts of pulsation for the third setup.

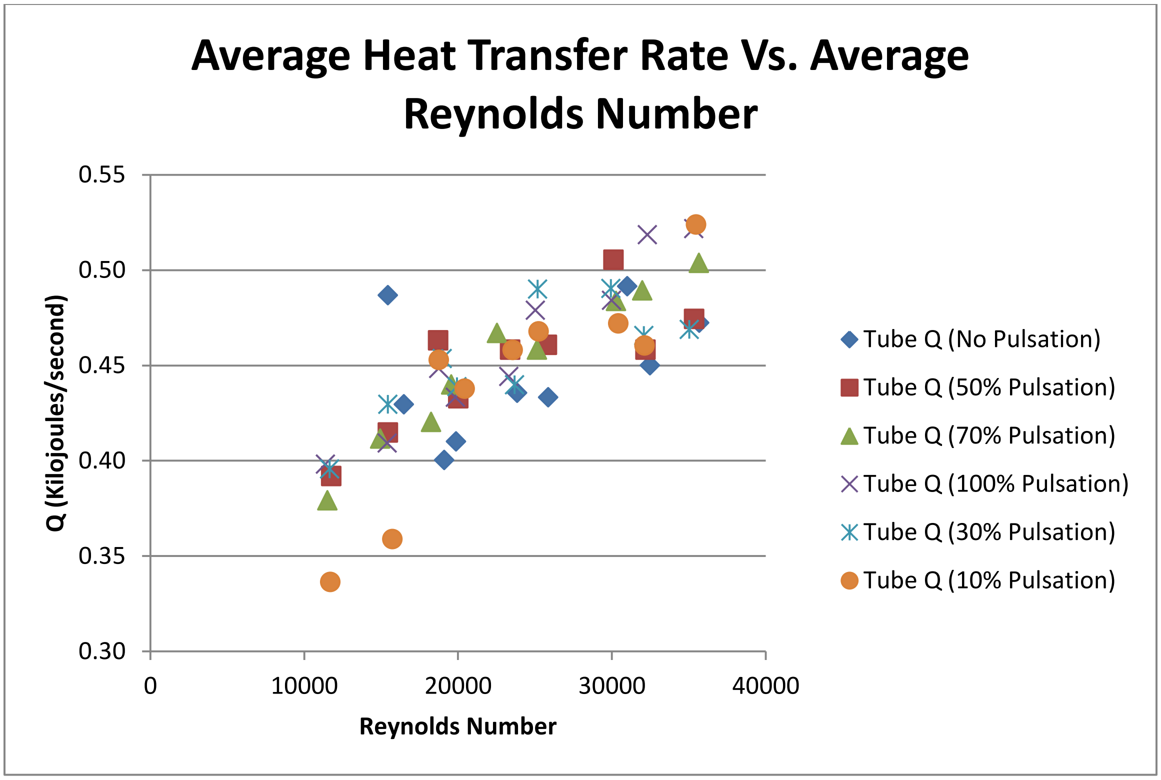

Figure 21: Data for the average heat gained in the tube with varying amounts of pulsation for the third setup.

Figure 21 shows that, in general, when pulsation is used the heat transfer rate to the tube is increased. However, there are a few things to note. The first point taken without pulsation is abnormally high, and the second point is higher than expected. This may be due to the system not being at steady state because these points were taken right after start up. Additionally, there is another point at Reynolds number 30000 which is higher than expected and does not follow the trend. Figures 22-26 show the percentage increase in heat transfer to the tube when the different amounts of pulsation are used compared to when pulsation is not used. The first two points will be excluded due to the abnormally high reading for the first two points without pulsation.

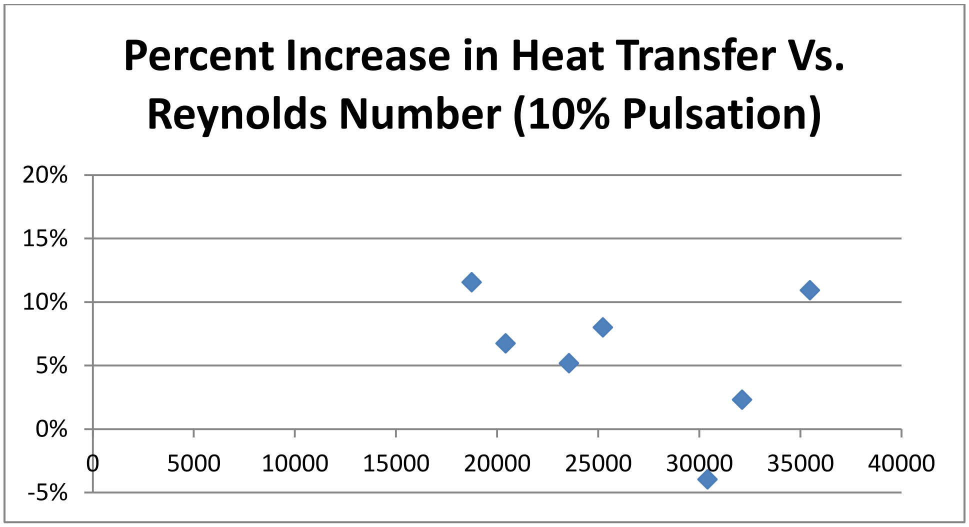

Figure 22: Percent increase in heat transferred to the tube when 10% pulsation is used compared to when it is not.

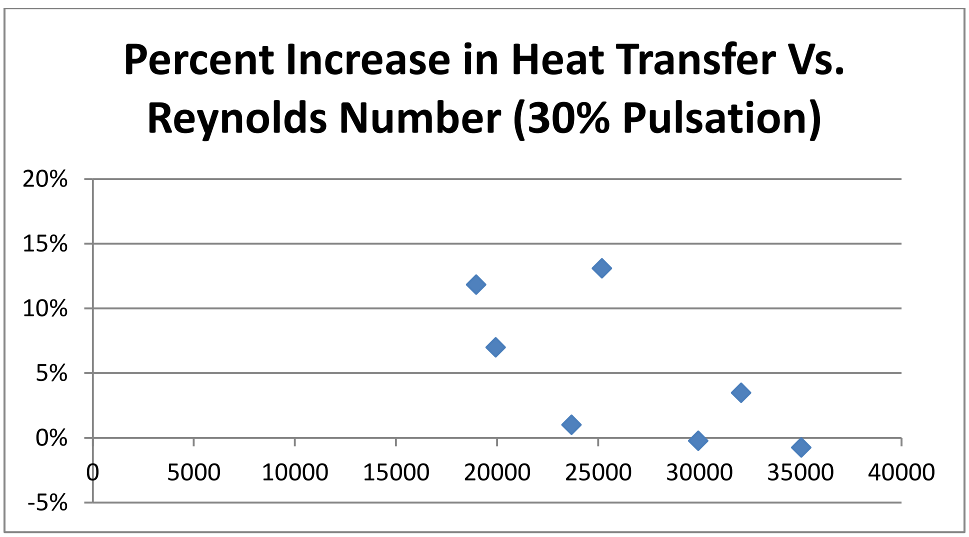

Figure 23: Percent increase in heat transferred to the tube when 30% pulsation is used compared to when it is not.

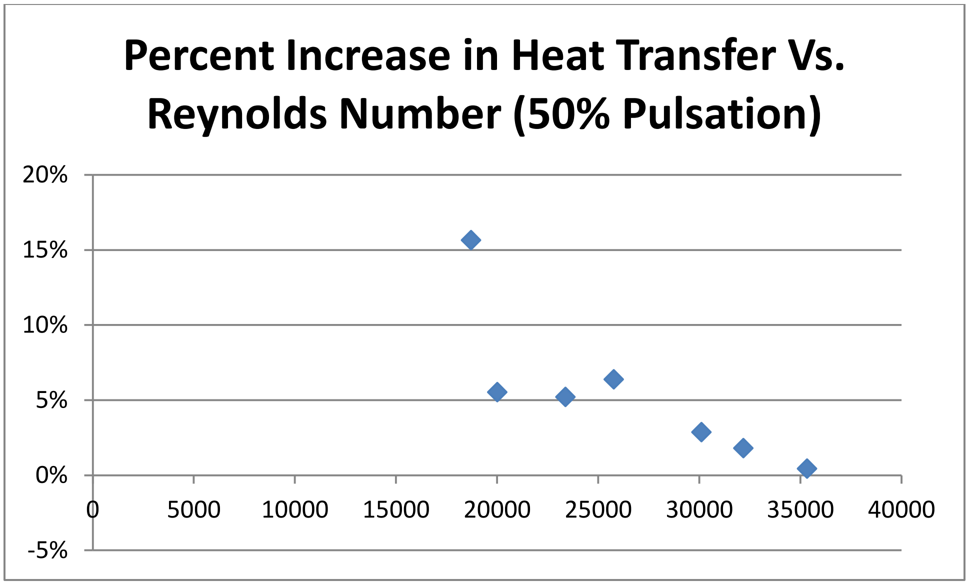

Figure 24: Percent increase in heat transferred to the tube when 50% pulsation is used compared to when it is not.

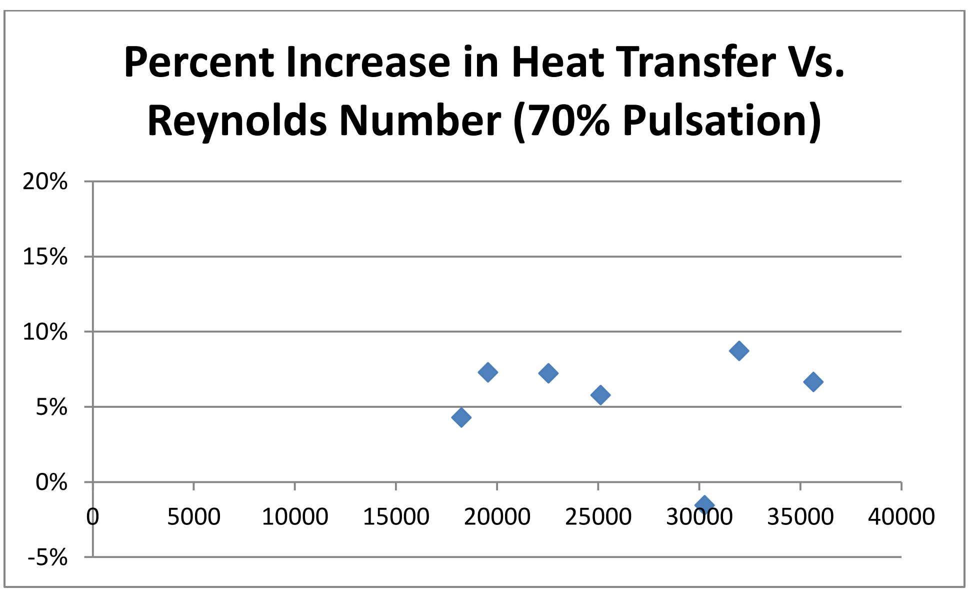

Figure 25: Percent increase in heat transferred to the tube when 70% pulsation is used compared to when it is not.

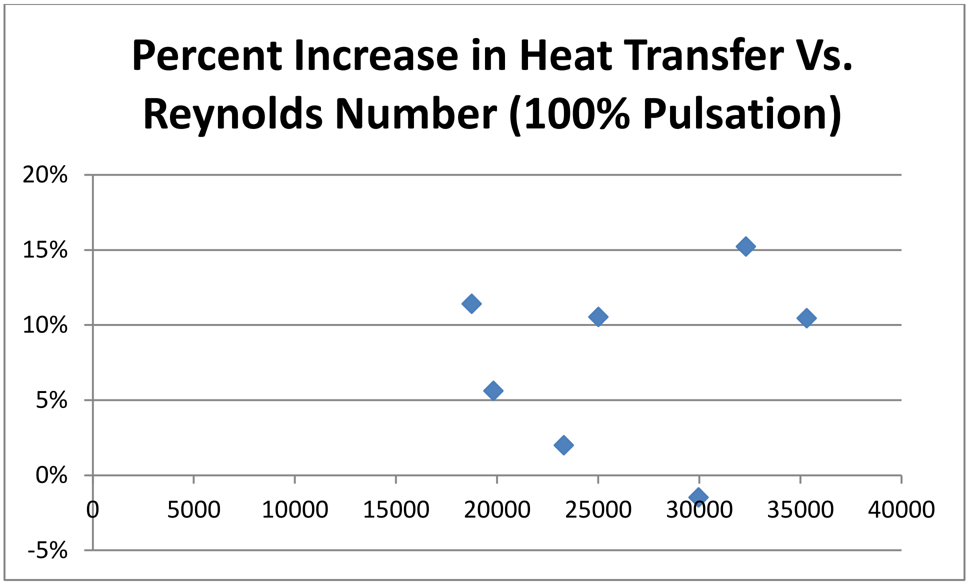

Figure 26: Percent increase in heat transferred to the tube when 100% pulsation is used compared to when it is not.

Figures 22-26 show that pulsation does increase the amount of heat transferred to the tube up to 15%. However a trend between frequency of pulsation and increasing heat transfer is not as clear. The average increase in percent heat transfer was calculated for each set of data and plotted on Figure 27 below.

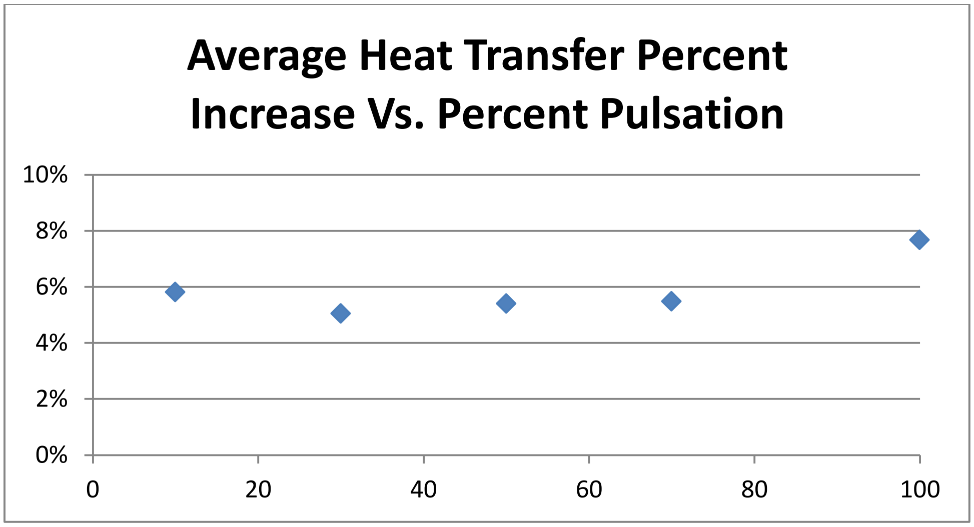

Figure 27: Average percent increase of heat transfer to the tube versus amount of pulsation.

Figure 27 shows that with the exception of the data obtained for 10% pulsation, the average percent of increase in heat transfer to the tube increases as the frequency increases.

Chapter 6: Conclusions and Future Recommendations

6.1 Conclusions

The first setup used to attempt to increase heat transfer using pulsation was unsuccessful. Measurements of the heat transfer to the tube decreased when using pulsation for every Reynolds number in the 10000 or greater range. This decrease in heat transfer was unexpected, but the lack of increase in heat transfer may have been due to the setup. The length of pipe going from where the fluid enters the piston pump to where it is injected before the heat exchanger was very long. As the fluid traveled from the pump to the inlet, it lost pressure. The decrease in pressure led to a decrease in amplitude of the pulses.

The decrease in heat transfer might also have been due to the piston pump taking fluid from a source that had a non-uniform temperature. The temperature of the fluid in the 6 liter holding tank was higher than the temperature of the fluid entering the heat exchanger as it had previously gone through the heat exchanger – and was therefore hot - while the fluid entering the heat exchanger was cooled by city water. Also, when pulsation is used, backwards flow is possible. This could cause the warm fluid injected by the piston pump to be read by the thermocouple, leading to a higher temperature reading than was representative of the rest of the fluid in the tube. The higher temperature at the inlet led to a measurement that indicated a decrease in heat transfer. Thus, even if the pulsation with this setup increased heat transfer, it would be impossible to tell because of the unrepresentative inlet temperature reading.

The second setup showed an increase in heat transfer when pulsatile flow was used compared to when it was not. The precision of the data points for this setup was better compared to the first setup. This improved precision is believed to be due to the temperature of the fluid being injected by the piston pump being the same temperature as the bulk fluid in the tube. Additionally, the improvement in precision was due to shortening the length of tube the fluid had to travel from the piston pump to the injection point.

The third setup was found to also be effective at increasing heat transfer with pulsatile flow. A range of pulsation frequencies were tested and in general as the frequency of the pulses increased, the heat transferred to the tube increased. The only exception to this was when 10% pulsation was used.

6.2 Future Recommendations

Several recommendations should be followed to obtain improved results compared to the results obtained in this thesis. The recirculating loop should be in a temperature controlled environment. As mentioned previously, the thermocouples used in this research used cold junction compensation which required a baseline temperature to measure temperature accurately. These thermocouples were open to the atmosphere causing the cold junction compensation to not read a constant temperature. A temperature controlled environment would lead to more accurate temperature readings and would reduce the amount of time spent on calibration.

The thermocouples used in this research were not able to measure temperature at the level of accuracy required. The thermocouples were Omega model TMQSS-062U. The best class of thermocouple of this model is only rated at $\pm$ 1 degree Celsius [16]. This uncertainty is too large. If a temperature reading is off by 1 degree, it would result in a very large percent error. An acceptable error range for thermocouples would be $\pm$ 0.05 degrees Celsius. Thermocouples do not typically measure with this accuracy, therefore a different temperature measuring device should be considered. Resistance Temperature Detectors (RTD) or thermistors would be possible replacements. RTDs and thermistors have a much smaller error ranges than a thermocouple.

The experimental setup would also benefit from using a different data acquisition system. The current data acquisition system is over ten years old. Several complications were encountered such as resistors burning out which took up valuable time. Breakdowns would be much less likely with a newer data acquisition system.

The current pulsating pump has a small amplitude that cannot be changed. A new pump should be obtained which has the ability to have variable amplitude so the effect of amplitude can be tested in pulsating flow. If this is done, the pressure increase due to the pulsation must be tracked because it could go higher than the rated psi for the tubing.

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